"The Efficiency of Man, or Economic Coefficient of the Human Machine." By W. MARCET, M.D., F.R.S., and R. B. FLORIS F.C.S. Received February 3,—Read February 23, 1899.

(From the Physiological Laboratory, University College, London.)

In a paper communicated by one of us, in April last, to the Royal Society,* a calorimeter was described for determining the heat emitted by man, which, on being tested, was found to give very reliable results. At the same time a short history was added of the various instruments used by physiologists to estimate the heat given out by man and animals; from that list was accidentally omitted the calorimeter of D'Arsonval.†

This calorimeter consists of two cylindrical concentric vessels, with an air space between them, and standing in an annular groove full of water, thus making an air-tight joint. The outer chamber (annular space) has a manometer connected with it which registers in a graphic way the variations of pressure in that chamber throughout the experiment. The subject of the experiment is enclosed in the inner chamber into which fresh air is continually being drawn by means of a flue where a gas burner is kept alight. The whole apparatus is suspended from the ceiling by a pulley, and balanced with a weight. It might be recollected that Marcet's calorimeter which we made use of, consists of a wooden chamber covered with felt inside and out, enclosing another made of sheet copper, carefully polished inside, with an air space between them. The size of the inner chamber is sufficient to admit of a person sitting down comfortably on a chair, with free elbow and head room. Two ventilators (agitators), worked by electric motors, constantly mix up the air inside the calorimeter, while the air from one of these ventilators impinges on a trough full of ice; the water from the melted ice is collected in a flask, and its temperature read at the end of the experiment.

Thermometers with stems projecting above the chambers show the temperature of the air in the copper chamber and the annular space, and another gives the temperature of the copper walls; these thermometers are divided into fiftieths of a degree centigrade. For further particulars we beg to refer to the original paper. The amount of heat evolved is easily calculated from the weight of ice melted, the temperature of the resulting water, and the change of temperature of the chamber, the annular space, and the copper.

Test experiments, made by means of the combustion of hydrogen

* "A Calorimeter for the Human Body," by W. Marcet, 'Roy. Soc. Proc.,' vol. 63.

† 'Travaux du Laboratoire de Marey,' 1878–79.

gas, gave a figure (34,428 calories) almost identical with that found by Favre and Silbermann (34,462).

After having used that instrument towards the estimation of the heat given out in a state of rest,* it appeared to us of interest to apply it to the determination of the heat emitted under exercise, so as to obtain finally a figure for the mechanical energy of the human machine, or, as termed by Verdet in his book on the 'Mechanical Theory of Heat,'† the economic coefficient of the human machine.

In 1861 Helmholtz, making use of Edward Smith's experiments on the treadmill, calculated by an ingenious mode of argument what ought to be the value of this coefficient. He reasoned in the following way‡:—A man in a state of repose emits exactly, in one hour, the amount of heat that would be required theoretically to raise his body uphill to a height of 522 m., which he looks upon as a fair rate of climbing in one hour; but, in order to accomplish this work, he would expire five times as much CO_2 as in the state of repose, and, therefore, produce five times as much heat, consequently the relation is 1 : 5, and therefore the economic coefficient would be 1/5.

Following this mode of argument, it will be readily seen that the supposed subject of this experiment, taking as an average weight 65 kilos., would have to emit in the state of rest 80·2 cals. per hour, because, on multiplying 80·2 by 423 (the mechanical equivalent of heat), the result would give 33,925 kilo.-metres; on the other hand, a man weighing 65 kilos. while raising his body by 522 m., would effect an amount of work = 33,930 kilo.-metres. Therefore the heat emitted in a state of rest in one hour would be exactly the same as the theoretical heat necessary to raise the body 522 m.; but as (according to Helmholtz) Edward Smith says it is necessary to give out five times more CO_2 than when at rest, to do that work, the coefficient will be 1/5.

This argument can be criticised as follows:—

1. Most authors give a little over 100 cals. per hour as the mean amount of heat emitted by a person in a state of repose, while, from ninety-two experiments on three different persons, we found from 79·056 cals. to 137·636 cals. with a mean of 102·260 cals., these figures being very far from 80·2, which are required to fit the present theory.

2. An ascent of 522 m. (1712 feet) in an hour is more than anybody can do going uphill; such exercise might perhaps be kept up for a minute or two, but the average height a man can ascend is usually put down at 1000 feet per hour (perhaps 1200 feet). It is difficult to say what amount of air a man would breathe during such exercise, but it

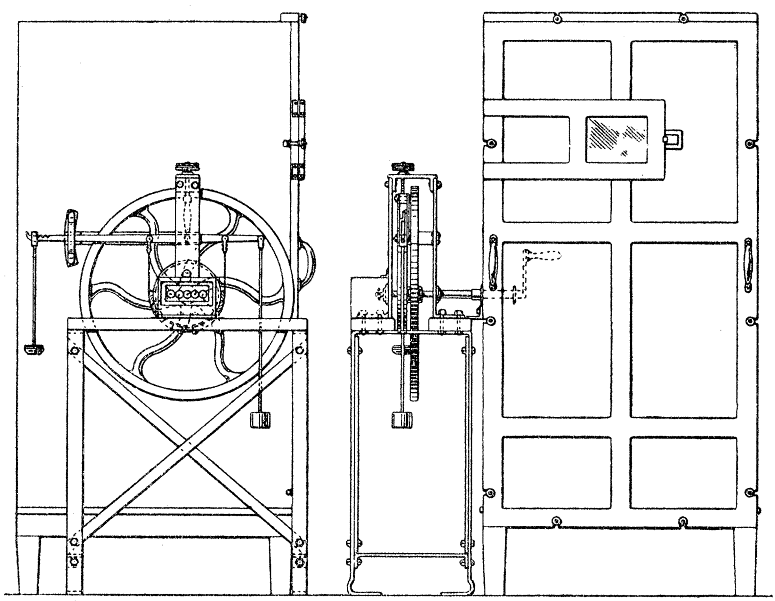
* 'Roy. Soc. Proc.,' vol. 63, p. 242.

† 'Verdet,' vol. 2, p. 250.

‡ "On the Application of the Law of the Conservation of Force to Organic Nature." Helmholtz. 'Proceedings of the Royal Institution,' vol. 3, p. 355, 1862.

would probably happen that if a person could climb at the rate of 522 m. per hour, as Smith did on the treadmill, then he would expire about five times as much CO_2 as in the state of repose; there is no reference to the oxygen absorbed in addition to the carbonic acid expired. From these considerations it will be understood how Helmholtz obtained the figure accepted in a general way as the value of the efficiency of the human body, and which is close to the figure we have found.

In order to determine experimentally the heat given out under a definite exercise, and ascertain that utilised in the work done, a brake was used, being a modification of that known to engineers as Pronié's. This brake (see diagram) consists of an iron fly-wheel resting on an iron stand and worked by a handle projecting inside the calorimeter through a stuffing box; a counter registers the number of revolutions throughout the experiment. The wheel is brought into contact with a semicircle of hard wood in sections fastened to a strap; by tightening this strap the semicircle of wood can be pressed more or less against the wheel, and thus the friction can be regulated.



On turning the wheel pressing against the wooden blocks, the tendency would be to give the blocks a revolving motion, but the force applied, instead of carrying them round and round, causes the wheel to slip over their surface, and in doing so to exert a degree of friction sufficient to raise a lever weighted at the end, and maintain it in a horizontal position as long as the wheel is rotated.

Therefore the power necessary to overcome the friction is exactly balanced by the weight at the end of the lever, and the work done will be a function of the weight multiplied by the length of the lever, or may be expressed as the work done in raising the weight by means of a cord wound round a drum, having for its radius the distance between the suspension of the lever and the end of the beam where the weight is hung. It should be understood that the beam is balanced by a counterpoise before the weight is suspended to its extremity.

The only objection that could be made to the use of this instrument might be the friction to overcome on turning the wheel; but there is no appreciable friction, the wheel revolving on ball-bearings like those of a bicycle. The weight can be altered, and it will be readily found that if a person works the wheel as hard as he can for a given time, by doubling the weight at the end of the lever the number of revolutions he can make in that same time will be half that registered with the lighter weight.

The experiment in the calorimeter is made as follows:—

The subject is shut up in the chamber as usual, and there he remains for thirty minutes quite quiet; during that time the temperatures are recorded, and the water from the melted ice is collected, thus the heat given out in the state of repose is determined. Then the person is let out of the calorimeter, and the chamber left full open for its ventilation, and about twenty minutes later he returns into the chamber. At once the work of turning the handle begins, to be continued for about half an hour. Then a rest is taken for another half hour inside the calorimeter, and the experiment is over.

By so doing the heat emitted in the state of rest is first determined; this is followed by the determination of the heat given out when at work and while the body is returning to its normal state of rest. It might be thought that the amount of work done had better be determined by first working the wheel perfectly free and therefore effecting no work, and then putting on the brake while the lever is weighted and doing a certain amount of work; the heat emitted in the first case would be subtracted from that given out in the second. This plan, however, is not admissible, because, at any rate, no work can be done without moving the arm, so that the arm is a necessary factor of the work.

The first question was to ascertain whether the mean relation of the oxygen absorbed under work to the calories emitted was the same as the corresponding mean relation in the state of rest. In order to settle this point, the CO_2 emitted and O absorbed were determined while in the calorimeter, together with the calories, both when sitting quiet and during exercise, the relation at rest having been fully investigated in our last paper and found to be 1 : 4·000.*

* It was stated in the previous paper that Hirn had found that while sitting quiet, 1 gram of oxygen gave rise to a mean of 5·22 calories.

The experiment was carried out by inspiring the external air through a nasal tube and expiring through a mouth-piece into bell-jar receivers suspended over water.*

The following are the results obtained :—

Relation between the Oxygen absorbed and the Heat emitted during Work.

Total calories during work.					
	Calories emitted during work.	Number of turns of wheel, 1 turn = 1·471 kilogram-metres.	Calories absorbed during work (theoretical).	Oxygen absorbed during work.	Calories for 1 gram oxygen absorbed.
				grams.	
W. M.	51·835	836	2·904	17·236	3·176
	52·776	812	2·820	18·698	2·973
	51·313	807	2·803	16·810	3·219
	52·367	771	2·678	18·875	2·916
				Mean....	3·071
R. B. F.	145·147	2870	9·967	48·348	3·208
	123·120	2306	8·009	36·992	3·545
	124·283	2147	7·457	37·190	3·542
	106·305	2102	7·300	35·246	3·223
	124·301	2275	7·901	37·930	3·486
				Mean....	3·401
E. R.	64·094	1097	3·810	24·767	2·742
	68·129	1041	3·616	21·012	3·414
	65·057	945	3·282	22·595	3·025
	58·554	839	2·914	19·455	3·160
	135·488	2174	7·550	42·704	3·349
	141·815	2170	7·536	44·029	3·392
	130·002	2379	8·262	46·343	2·984
	131·698	1976	6·863	44·821	3·091
	136·970	2050	7·119	43·339	3·325
	137·584	1969	6·838	43·496	3·320
	140·579	2198	7·634	45·715	3·242
	140·192	2064	7·168	41·139	3·582
	136·936	2092	7·266	42·377	3·403
	150·881	2151	7·470	43·083	3·676
				Mean....	3·265

Consequently the oxygen absorbed does not follow exactly the amount of heat produced; but a number of experiments for separate individuals show in each case means somewhat approximating each other, though less obviously than in the state of rest.

* The persons who submitted to these experiments had practised this mode of breathing for a considerable time, and it had become with them quite natural.

The present inquiry includes twenty-three experiments :—

	Gram O.	Calories.
The first set of four experiments on W.M. gave......	1	3·071
The second set of five experiments on R. B. F. gave	1	3·401
The third set of fourteen experiments on E. R. gave	1	3·265
Mean	1	3·246

Therefore it will be readily seen that 1 gram of oxygen will give rise to more heat in a state of rest (1 : 4·000) than under exercise (1 : 3·246), and it cannot be admitted that the same mean amount of heat is produced by a given weight of oxygen absorbed in repose and under exercise; Hirn observed a similar occurrence. It may therefore be concluded that the human body in the state of rest makes a more efficient use of its oxygen than it does under exercise in the proportion of about 4·000 : 3·246.

The next, and perhaps most important subject for consideration, is the efficiency or economic coefficient of the human machine.

The efficiency of the body as a machine is the relation between the theoretical heat corresponding to the work done* and the actual amount of heat that the body requires to do this work. According to this definition the result sought for in our inquiries was obtained by dividing the theoretical amount of heat necessary for the work done in each experiment by the heat given out during the work, less the normal heat emitted in the same time plus the theoretical heat necessary for the work. This statement can be expressed in the form of a formula.

If

E = Efficiency of the human machine.
T = Theoretical calories necessary for the work done,
C = Heat emitted during the work,
c = Heat emitted in a state of rest,

then

$$E = \frac{T}{C - c + T}.$$

The weight suspended from the end of the lever forming part of the brake was 485 grams, and knowing the length of the lever (48·275 cm.) it was easy to calculate that each turn of the wheel performed an invariable amount of work = 1·471 kilogram-metres.

* Mechanical equivalent of heat multiplied by work done in kilogram-metres.

Table showing the Efficiency (Economic Coefficient) of the Human Machine.

W. M. under Experiment.

Calories emitted in state of rest.	Calories emitted during work, followed by rest for an equal time.	Revolutions of the wheel.	Work done in kilogram-metres.	Calories, theoretical, corresponding to work done.	Heat utilised, *i.e.*, efficiency.
½ hour.					
39·872	51·835	836	1230	2·904	0·195
40·786	52·776	812	1194	2·820	0·190
40·261	51·313	807	1187	2·803	0·203
43·369	52·367	771	1134	2·678	0·229
52·703	65·801	704	1036	2·445	0·157
59·135	70·012	894	1315	3·105	0·222
45·127	59·715	361*	1035	2·443	0·143
Mean 45·893	57·688		1162	2·743	0·191
1 hour.					
87·010	104·720	1556	2289	5·405	0·234

R. B. F. under Experiment.

Calories emitted in state of rest.	Calories emitted during work, followed by rest for an equal time.	Revolutions of the wheel.	Work done in kilogram-metres.	Calories, theoretical, corresponding to work done.	Heat utilised, *i.e.*, efficiency.
½ hour.					
43·745	85·717	1670	2457	5·801	0·121
43·887	70·311	1269	1867	4·408	0·143
45·087	70·643	1003	1475	3·484	0·120
50·284	60·269	1023	1505	3·552	0·261
36·839	59·121	911	1340	3·164	0·124
45·165	75·362	1228	1806	4·265	0·124
42·708	56·927	620*	1777	4·196	0·228
Mean 43·959	68·336		1747	4·124	
1 hour.					
93·594	113·428	1811	2664	6·291	0·241
90·166	135·607	2176	3201	7·559	0·142
97·786	136·097	2278	3351	7·913	0·171
97·760	140·845	2570	3780	8·928	0·172
93·512	133·238	2299	3382	7·985	0·167
87·408	128·783	2694	3963	9·357	0·184
101·696	141·524	2509	3691	8·714	0·180
83·684	145·147	2870	4222	9·967	0·140
80·976	123·120	2306	3392	8·009	0·160
85·210	124·283	2147	3158	7·457	0·160
80·496	106·305	2102	3092	7·300	0·220
104·244	124·301	2275	3346	9·901	0·283
Mean 91·378	129·390		3437	8·115	0·176

* Double weight on brake.

E. R. under Experiment.

Calories emitted in state of rest.	Calories emitted during work, followed by rest for an equal time.	Revolutions of the wheel.	Work done in kilogram-metres.	Calories, theoretical, corresponding to work done.	Heat utilised, *i.e.*, efficiency.
½ hour.					
47·283	58·554	839	1234	2·914	0·205
51·963	65·057	945	1390	3·282	0·200
52·207	68·129	1041	1531	3·616	0·185
46·746	64·094	1097	1614	3·810	0·180
61·975	83·010	1055	1552	3·664	0·148
53·801	88·244	1248	1542	4·335	0·112
Mean 52·329	71·181		1477	3·603	
1 hour.					
136·608	162·132	2482	3651	8·622	0·252
130·208	178·722	2582	3798	8·969	0·156
115·868	172·443	2551	3753	8·861	0·135
133·392	194·626	2689	3956	9·339	0·132
137·636	177·412	2545	3744	8·839	0·182
128·578	177·915	2340	3442	8·127	0·141
107·355	137·584	1969	2896	6·838	0·184
102·545	140·579	2198	3233	7·634	0·167
114·885	140·192	2064	3036	7·168	0·221
107·783	136·936	2092	3077	7·266	0·200
113·451	150·881	2151	3164	7·470	0·166
Mean 120·755	160·857		3432	8·103	0·174

E. F. under Experiment.

Calories emitted in state of rest.	Calories emitted during ½ hr. work, followed by ½ hr. rest.	Revolutions of the wheel.	Work done in kilogram-metres.	Calories, theoretical, corresponding to work done.	Heat utilised, *i.e.*, efficiency.
1 hour.					
101·090	121·099	1892	2783	6·572	0·247
120·418	147·723	2242	3298	7·788	0·222
119·822	157·280	2287	3364	7·944	0·175
101·758	153·264	2335	3435	8·111	0·136
102·302	152·476	2170	3192	7·538	0·131
105·774	149·040	2302	3386	7·997	0·156
110·220	130·701	1499	2205	5·207	0·203
101·752	123·203	1527	2246	5·303	0·198
102·582	164·413	2445	3597	8·492	0·121
104·642	119·885	1761	2590	6·116	0·286
112·140	144·660	2007	2952	6·971	0·176
108·557	168·365	2444	3595	8·489	0·124
101·160	161·014	2427	3570	8·430	0·123
96·078	133·818	2008	2954	6·974	0·156
119·860	144·226	2046	3010	7·104	0·226
120·800	148·591	2114	3110	7·342	0·209
108·056	144·985		3080	6·684	0·181

M. (Woman) under Experiment.

Calories emitted in state of rest.	Calories emitted during ½ hr. work, followed by ½ hr. rest.	Revolutions of the wheel.	Work done, in kilogram-metres.	Calories, theoretical, corresponding to work done.	Heat utilised, *i.e.*, efficiency.
1 hour					
85·546	116·644	2303	3388	7·999	0·204
84·036	127·086	2543	3741	8·832	0·170
64·140	108·836	2522	3710	8·759	0·164
78·750	110·703	2231	3282	7·748	0·195
78·576	114·899	2370	3486	8·231	0·185
78·094	109·205	2363	3476	8·207	0·209
77·374	102·955	2165	3185	7·520	0·227
Mean 78·074	112·904		3467	8·185	0·193

The five tables include sixty-seven experiments, being all those made (seventy-one in number) with the exception of four; these, which were undertaken on four consecutive days, when the work was resumed last autumn, yielded for the value of the efficiency, at any rate in three cases, figures obviously much too high, and which have been omitted on that account; they were the following:—for E. R., 0·462, 0·231, 0·384, 0·363. These irregularities are apparently due to some accidental mis-estimation of the water from the melted ice.

In every case, as will be readily seen from the foregoing tables, the amount of heat emitted under exercise is largely in excess of that given out in a state of rest during the same time; this excess, in the case of the five persons under experiment, amounted to

In thirty minutes.	Per cent. of normal.	Calories excess + theoretical for 1000 kilogram-metres.
11·795 cal. for W. M.	25·7	12·511
24·377 „ „ R. B. F.	55·5	16·314
18·852 „ „ E. R.	36·0	15·203
In one hour.		
38·012 cal. for R. B. F.	41·6	13·421
40·102 „ „ E. R.	33·2	14·046
36·929 „ „ E. F.	34·2	14·159
34·830 „ „ M.	44·6	12·407

From a consideration of the foregoing tables it will be seen that the inquiry as to efficiency, made on five different persons, yielded the following results:—

	Age.	Weight.	Occupation.	Efficiency.	No. of Experiments.
		kilos.			
W. M.	69	57·9	Laboratory work	0·191	7
R. B. F.	28	53·0	,, ,,	0·176	19
E. R.........	29	80·4	,, ,,	0·174	17
E. F.........	16	..	,, ,,	0·181	16
M. (woman)..	47	..	Charwoman	0·193	7
			Mean	0·183	66

Therefore the maximum mean efficiency was 0·193 in the case of the woman from seven experiments, and the minimum mean efficiency was 0·174 for E. R. from seventeen experiments; the general mean from five different persons was 0·183.

The general results obtained from this inquiry can be summarised as follows :—

(1) There is no fixed relation per individual experiment between the oxygen absorbed under excercise and the corresponding heat emitted, although the mean for each person somewhat approximates a constant figure which is 1 to 3·246. Considering that in the state of rest we found the corresponding ratio to be 1 to 4·000, it may be concluded that the oxygen is better utilised for the production of heat in a state of rest than under exercise.

(2) There is a marked excess of heat over normal given out under exercise, this excess (+ theoretical heat) produced in doing a definite amount of work (say 1000 kilogram-metres) varies for each of the five persons under experiment.

(3) The efficiency, or economic coefficient, for the five persons under experiment varied from 0·193 to 0·174 with a mean of 0·183; or 18·3 per cent. of the excess heat produced + the theoretical heat corresponding to the work done. This is a little less than a fifth.

"Some Experiments bearing on the Theory of Voltaic Action." By J. Brown. Communicated by Professor Everett, F.R.S.

Received February 4,—Read February 23, 1899.

In former papers on the "Theory of Voltaic Action,"* I have adduced evidence in support of the view that the difference of electric potential observed near the surface of two metals in contact is caused, or at all events mainly influenced, by the chemical activity of films

* 'Phil. Mag.,' vol. 6 (1878), p. 142; *ibid.*, vol. 7 (1879), p. 109; 'Roy. Soc. Proc.,' vol. 41 (1886), p. 294.